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CHAPTER 5.3
INVESTMENT CASTINGS

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THE PROCESS

Investment casting (sometimes called the *lost-wax process*) utilizes a one-piece ceramic mold. The mold is made by surrounding a wax or plastic replica of the part with ceramic material. After the ceramic material solidifies, the wax replica is melted out, and metal is poured into the resulting cavity.

There are two basic mold-making variations: (1) the *monolithic method,* which utilizes a solid mold contained by a stainless steel or Inconel flask, and (2) the *shell method,* which utilizes a thin-walled (about 6-mm- or ¼-in-thick) mold and no flask. (See Fig. 5.3.1.)

The complete sequence for making investment castings with the shell method is as follows:

1. Wax or plastic patterns are injection-molded. When wax is used, the molds can be inexpensive, being made from a low-temperature alloy sprayed or cast around a master-part pattern. The pattern is made with an allowance for shrinkage.
2. Patterns with gates and runners are assembled to form a "tree."
3. The tree is dipped into a slurry of fine ceramic material.
4. Refractory grain is sifted onto the coated pattern with a "rainfall coater" or by fluidized bed.
5. The coat of slurry and grain is dried with air. Typically, this requires 2 h in an environment with considerable air movement and relative humidity of 50 percent or less.
6. Steps 3, 4, and 5 are repeated with successively coarser refractory material to a thickness of 5 to 8 mm ($^{3}/_{16}$ to $^{1}/_{3}$ in) depending on the size of the casting tree. A final dip in the slurry material provides a sealing coating.
7. The coated tree is thoroughly dried. The pattern, gate, and sprue material is melted out of the mold by inverting (sprue opening down) and heating it in an autoclave or oven for about 5 to 10 min.

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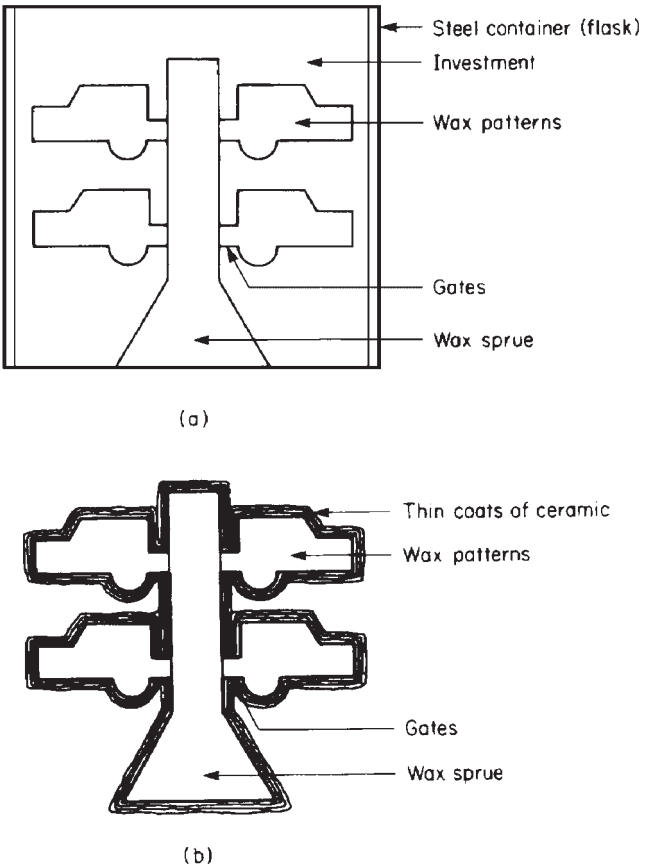

FIGURE 5.3.1 Molds for investment casting: (*a*) monolithic or solid mold before wax is removed; (*b*) shell mold before wax is removed.

8. The mold is burned out to remove all traces of wax or plastic and to cure the investment. The burnout temperature is typically 980°C (1800°F) for a minimum of 2 h.
9. Hot molds are filled with molten metal by gravity, pressure, vacuum-assist, or centrifugal force.
10. Shake out: After the mold cools and the cast metal solidifies, the mold material is removed from the tree, typically with an air-powered hammer or vibratory machine.
11. The tree is descaled. This is achieved by immersing the tree for 10 to 15 min in a 600°C (1100°F) caustic salt bath followed by an immediate cold-water dip and then neutralizing and cleaning rinses.
12. Parts are removed from the tree by bandsaw or abrasive wheel.
13. Gates are removed from the parts by means of a grinding wheel, abrasive belt,

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milling machine, or lathe.

Current practice often involves robotic handling of the shells and automation of the various steps. This provides advantages of cost, consistency, and uniformity of the coatings. However, where applicable, manual methods are still used.

The process for monolithic (solid) molds is very similar, the difference being that the mold is first coated and then inserted in a flask, which is then filled with investment material.

The shell process is better adapted to larger parts and has a shorter cycle time. It also has the advantage of less tendency of surface decarburization of the cast part. On the other hand, mold cracking is more likely, especially with plastic patterns. In addition, detail definition at the part surface may be poorer because of more rapid cooling of the melted metal.

TYPICAL CHARACTERISTICS AND APPLICATIONS

Historically, investment castings most likely were specified when the following part characteristics were involved: intricate shape, close tolerances, small size, and high-strength alloys. Costs of the investment material and other items inhibited its use for larger castings. However, advances in the process involving greater use of the shell method and with robotic assist have reduced the cost differential with other casting processes, especially for larger sizes. Investment castings currently range in size from 1 g (0.035 oz) to upwards of 90 kg (200 lb).

Investment castings are most likely to be used when the shape of the part involves contoured surfaces, undercuts, and other intricacies that make machining difficult or unfeasible. They are used for mechanical components in such products as sewing machines, business machines, firearms, and surgical and dental devices. Turbine blades, valve bodies, ratchets, cams, pawls, gears, hose fittings, cranks, levers, vanes, connectors, support rings, impellers, manifolds, hand tools, golf club heads, and radar waveguides are typical parts. Figure 5.3.2 shows a collection of typical investment-cast parts.

ECONOMIC PRODUCTION QUANTITIES

Investment casting is best suited to moderately low and medium production levels. In many cases in which machining would be extensive, however, it is applied successfully to high-production applications as well.

The process also can be used for prototype quantities by having the wax patterns made by stereolithography or another rapid prototyping process (with the necessary shrinkage allowances). Prototype parts can then be cast from these patterns using the normal investment casting process.

Tooling costs for wax patterns can be low, especially if the mold is made from a master pattern by using the spray or casting methods. The lowest-cost molds are made by spraying low-temperature alloys over the pattern. Such molds are used for wax patterns only and have a life of 800 to 1200 pieces. More nearly permanent soft-metal molds made by casting will have a life of up to 12,000 pieces.

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FIGURE 5.3.2 Collection of investment-cast parts. Note their complexity and size, as indicated by the 6-in ruler. (*Courtesy The Singer Company.*)

For still higher production levels, mold cavities are machined from aluminum or steel. Aluminum machined molds (for wax patterns) are quite inexpensive. With steel mold material and with multiple cavities, mold costs are the same as those for other injection-molded plastic parts.

Because of a high labor and indirect-materials content, the unit cost of investment castings tends to be higher than that of powder-metal, die-cast, or other parts made from alternative high-production methods. There are exceptions, when a part is particularly complex or of a configuration or material that is not suitable for other processes, but generally, economical quantities for investment castings do not extend to mass-production situations.

GENERAL DESIGN CONSIDERATIONS

Perhaps the greatest advantage of investment castings is the high degree of design freedom that they permit. Complex shapes that would be too costly to machine can be produced quickly and economically as investment castings. In many cases, what would otherwise be two or more separate parts can be designed as one integral casting, eliminating assembly operations. The process also allows designers to select from a wide range of alloys. Ideally, the time for deciding if a part is to be made by the investment-casting process is when it is on the drawing board. When designing for

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investment casting, designers should keep the toolmaker and investment caster in mind. They should remember that the pattern is injection-molded and therefore should observe good practices that apply to injection-molded parts. These include the use of a well-located, straight parting line, adequate draft, and avoidance of undercuts. Designers should use generous fillets and radii whenever possible. This not only makes a better-looking part but also produces a stronger one as well.

SUITABLE MATERIALS

A wide variety of metals, both ferrous and nonferrous, can be used to make investment castings. Any metal that is meltable in standard induction or gas furnaces can be used. Vacuum melting and pouring can be incorporated in the process if the metal used and its application require this step.

Materials that are not easily machinable are good candidates for some investment-casting applications because the process can provide dimensional precision and intricate shapes that would otherwise require machining. Table 5.3.1 lists a number of alloys with high-castability ratings.

DETAILED DESIGN RECOMMENDATIONS

Minimum Wall Thickness

The minimum thickness of casting walls is determined primarily by the fluidity of the metal to be cast. Another factor is the length of the section involved. If the section is long, a heavier wall may be required. Table 5.3.2 provides recommended minimum wall thicknesses for various investment-castable metals.

Flatness and Straightness

Deviations from flatness and straightness can be minimized if ribs and gussets are incorporated in the part. Because of pattern shrinkage, investment shrinkage, and metal shrinkage during solidification, there is always a tendency for an investment-cast part to "dish" (develop concave surfaces where flat surfaces are specified). This condition takes place in areas of thick cross section. As illustrated in Fig. 5.3.3, dishing can be minimized by designing parts with uniformly thin walls.

Radii

Although sharp corners are achievable, generous radii are preferred whenever possible. Ample fillets and radii facilitate die filling for the pattern and mold filling for the cast part and also tend to produce better-quality, more accurate parts. Although it is possible to cast sharper corners, a minimum fillet radius of 0.75 mm (0.030 in) should

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TABLE 5.3.1 Suitable Materials for Investment Casting

Material	Fluidity	Shrinkage	Resistance to hot tearing	Castability rating
Carbon steels				
1040 (G10400)	B	B	B	B+
1050 (G10500)	B	B	B	B+
1060 (G10600)	B	A	B	B+
Alloy steels				
2345 (G23450)	B	B	B	A−
4130 (G41300)	B	B	B	A−
4140 (G41400)	B	B	B	A−
4150 (G41500)	B	B	B	A−
4340 (G43400)	B	B	B	A−
4640 (G46400)	B	B	B	A−
6150 (G61500)	B	B	B	A−
8640 (G86400)	B	B	B	A−
8645 (G86450)	B	B	B	A−
Austenitic stainless steels				
302 (S30200)	A	A	A	A+
303 (S30300)	A	A	B	A
304 (S30400)	A	A	A	A+
316 (S31600)	A	A	A	A+
CF-8M (V92900)	A	A	A	A+
Ferritic stainless steels				
410 (S41000)	A	C	B	A
416 (S41600)	A	C	B	B+
430 (S43000)	A	C	B	A−
431 (S43100)	A	C	B	A−
Precipitation-hardening stainless steel				
17-4 PH (S17700)	A	C	B	B+
Nickel alloys				
Monel (QQ-N-288-A) (N04020)	A	B	B	B+
Inconel 600 (AMS 5665) (N06600)	A	B	B	B+
Cobalt alloys				
Cobalt 21 (R30021)	A	A	B	A−
Cobalt 31 (R30031)	A	A	B	A−
Aluminum alloys				
A 356 (A13560)	A	A	A	A+
C 355 (A33550)	A	A	A	A
Tool steels				
A-2 (T30102)	B	B	B	B+
H-13 (T20813)	B	B	B	B+
S-1 (T41901)	B	B	B	A−
S-2 (T41902)	B	B	B	A−
S-4 (T41904)	B	B	B	A−
S-5 (T41905)	B	B	B	A−
Copper alloys				
Gunmetal (C90500)	A	C	A	B+
Naval brass (C46400)	B	B	A	B+
Phosphor bronze (C94400)	B	B	A	B+
Red brass (C23000)	A	A	A	A−
Silicon brass (C87800)	A	A	A	A+
Beryllium copper 10C (C82000)	A	A	A	A
Beryllium copper 20C (C82500)	A	A	A	A+
Beryllium copper 30C (C82200)	A	A	A	A

Note: A = excellent; B = good; C = poor.

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TABLE 5.3.2 Suggested Minimum Wall Thickness for Various Investment-Casting Metals

Metal	Minimum wall thickness, mm (in)
Ferrous metals	
Low-carbon steel	1.8 (0.070)
High-carbon steel	1.5 (0.060)
Low-alloy steel	1.5 (0.060)
Stainless steel, 300 Series	1.0 (0.040)
Stainless steel, 400 Series	1.5 (0.060)
Cobalt-base alloys	0.75 (0.030)
Nonferrous metals	
Aluminum	1.0 (0.040)
Beryllium copper	0.75 (0.030)
Brass	1.0 (0.040)
Bronze	1.5 (0.060)

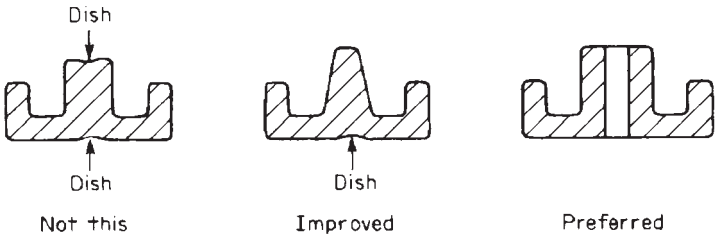

FIGURE 5.3.3 Keep walls uniformly thin to avoid "dishing."

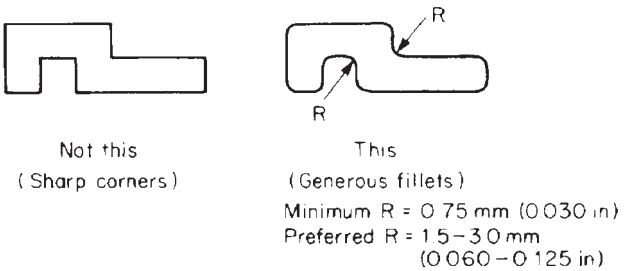

FIGURE 5.3.4 Use generous fillets and radii.

be specified, and even 1.5 to 3.0 mm (0.06 to 0.125 in) is preferable. (See Fig. 5.3.4.)

Curved Surfaces

Both convex and concave surfaces can be produced easily. However, concave surfaces

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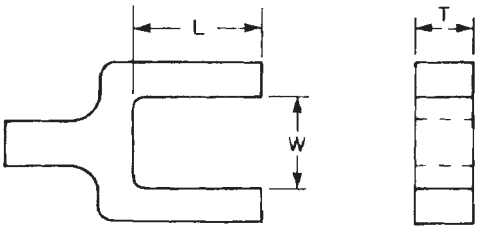

Thickness T, mm (in)	Minimum W, mm (in)
1.5 (1/16)	1.5 (1/16)
6 (1/4)	2.4 (3/32)
10 (3/8)	3 (1/8)
13 (1/2)	5 (3/16)
25 (1)	6 (1/4)

FIGURE 5.3.5 Forks and yokes have minimum practical slot widths.

can be cast to somewhat greater accuracy than convex surfaces because the cast metal, when solidifying and shrinking, hugs the mold instead of shrinking away from it.

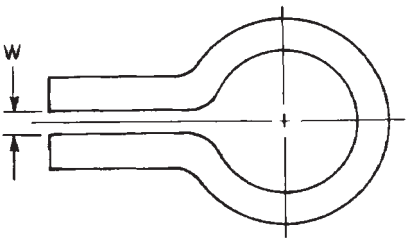

FIGURE 5.3.6 Minimum slot widths W for clamps and pinch collars are 1.5 mm (0.060 in) for ferrous metals and 1.0 mm (0.040 in) for nonferrous metals.

Parallel Sections

Parallel sections can be classified into two basic geometric types: (1) forks or yokes and (2) clamps or pinch collars. They each offer different challenges to the caster. See Fig. 5.3.5, where T represents the thickness, L the length of the tine of the fork, and W the inside width of the fork. As the thickness T increases, the width of the opening W also must increase so that the mold ceramic will fill the slot.

For clamps or pinch collars, as illustrated in Fig. 5.3.6, the minimum slot width W for ferrous metals is 1.5 mm (0.060 in) and for nonferrous metals is 1.0 mm (0.040 in).

Keys and Keyways

When keys and keyways are required, the desirable ratio of width to depth for ease of casting is 1.0 or more (see Fig. 5.3.7). The minimum castable key width is 2.3 mm (0.090 in) for ferrous metals and 1.5 mm (0.060 in) for nonferrous alloys.

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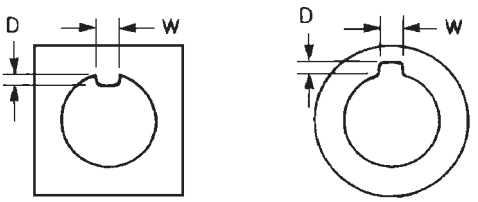

FIGURE 5.3.7 Keys and keyways should have a width-to-depth ratio of 1:1 or more. Keys should not be narrower than 2.3 mm (0.090 in) for ferrous metals and 1.5 mm (0.060 in) for nonferrous metals.

Holes

Holes can be incorporated into investment castings when required. However, it becomes impractical to cast when holes are less than 1.5 mm (0.060 in) in diameter for nonferrous alloys or less than 2.2 mm (0.087 in) for ferrous alloys.

Blind Holes

Blind holes usually are not recommended to be cast, since in many cases if the operator is not careful in precoating and investing the mold, air pockets that would cause globs of metal in the hole could be formed. However, if a blind hole is required, the length of depth should not exceed the diameter.

Through Holes

In most cases a through hole may be cast more economically than it can be produced by drilling after casting. Also, in many cases, by incorporating a hole in the casting, sinks or cavitation can be minimized, since the wall thickness is more uniform. The same tolerance applies for through holes as for blind holes. There is a definite ratio between the hole diameter D and the length of the hole L in through holes. This L/D ratio should not be greater than 4:1 in ferrous metals or 5:1 in copper and aluminum alloys.

Ceramic Cores

The use of ceramic cores makes intricate internal configurations of investment castings possible. This is particularly important for intricate blades or internal threads in materials that are not easily machinable. Once the metal has been cast, the cores are leached out. In designing pattern molds for a part to be made with a ceramic core, provision must be made in the mold to support the ceramic core when the wax is injected into the mold.

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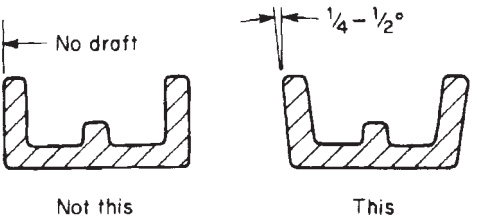

FIGURE 5.3.8 A small amount of draft is necessary for the removal of patterns from the molding die.

Draft

A small amount of draft is necessary to be able to remove wax patterns from the molding die; $\frac{1}{4}$ to $\frac{1}{8}°$ is adequate. (See Fig. 5.3.8.)

Screw Threads

Screw threads, both internal and external, can be investment-cast. In most cases, however, it is more satisfactory to machine them than to cast them. The major reasons for this are

1. Cast threads usually require a secondary chasing operation after casting to refine the surface and dimensions.
2. Threaded sections in wax or plastic patterns are a complicating factor in pattern making. If internal threads are cast, the threaded hole must be a through hole to allow removal of the investment material from the casting.

Undercuts

Undercuts pose no problem to the casting operation, but they do complicate the pattern-molding operation and therefore should be avoided if possible.

DIMENSIONAL FACTORS

By far the most significant factor influencing the dimensional accuracy of investment castings is the shrinkage of the materials used as they change from the molten to solid state. The wax or plastic pattern, the investment material, and the cast metal all exhibit this characteristic to some degree. Although these shrinkages are predictable, there are some variations in the amount of shrinkage and its effect on any part that result in some loss of dimensional accuracy. The effect of shrinkage is more evident in heavy-

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wall or unequal-wall sections. The following are normal shrinkage allowances to accommodate differences between master-pattern and final-part dimensions:

Shell-mold method: 1.6–1.7 percent

Flask-mold method: 1.1 percent

Other factors adversely affecting dimensional control are

- Temperature variations in pouring
- Fluidity of the metal used
- Pattern and pattern-mold dimensional variations
- Pattern distortion during handling
- Investment-mold cracks and other variations
- Wax shrinkage and sag over a period of time

RECOMMENDED TOLERANCES

Tolerance recommendations for angles, general dimensions, roundness, and flatness are shown in Fig. 5.3.9 and Tables 5.3.3 through 5.3.5.

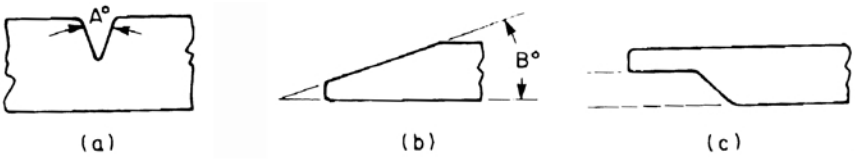

FIGURE 5.3.9 Recommended tolerances for angles: (*a*) angular openings as *A* (±1.5°); (*b*) angular shapes as *B* (±0.5°); (*c*) parallelism (±2.0°).

TABLE 5.3.3 General Dimensional Tolerances

	Recommended tolerance, mm (in)	
Dimension, mm (in)	Normal	Tight
Up to 6 (up to 0.25)	±0.4 (±0.015)	±0.08 (±0.003)
6–13 (0.25–0.50)	±0.4 (±0.015)	±0.10 (±0.004)
13–25 (0.50–1.0)	±0.4 (±0.015)	±0.13 (±0.005)
25–50 (1.0–2.0)	±0.4 (±0.015)	±0.18 (±0.007)
50–100 (2.0–4.0)	±0.8 (±0.030)	±0.40 (±0.015)
100–150 (4.0–6.0)	±1.1 (±0.045)	±0.60 (±0.025)
Over 150 (over 6.0)	±1.5 (±0.060)	±0.80 (+0.030)

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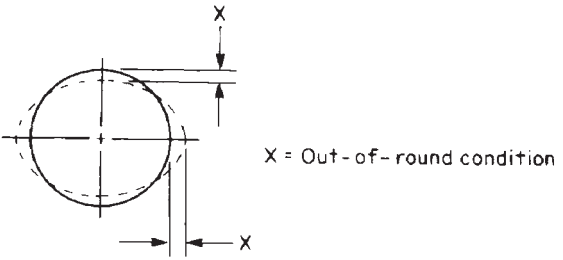
TABLE 5.3.4 Recommended Allowance for Out-of-Roundness: Round and Tubular Sections



Solid sections	
Nominal diameter, mm (in)	Recommended out-of-roundness allowance, mm (in)
Under 13 (under 0.5)	0.15 (0.006)
13–25 (0.5–1.0)	0.25 (0.010)
25–38 (1.0–1.5)	0.33 (0.013)
38–50 (1.5–2.0)	0.38 (0.015)
Hollow-tube sections	
Outside diameter, mm (in)	Recommended out-of-roundness allowance, mm (in)
Up to 25 (up to 1.0)	0.25 (0.010)
25–38 (1.0–1.5)	0.33 (0.013)
38–50 (1.5–2.0)	0.38 (0.015)
50–75 (2.0–3.0)	0.63 (0.025)

TABLE 5.3.5 Recommended Flatness and Straightness Tolerances

Length of section, mm (in)	Allowable deviation, mm (in)
Up to 6 (up to 0.25)	±0.05 (±0.002)
6–13 (0.25–0.50)	±0.10 (±0.004)
13–25 (0.50–1.00)	±0.20 (±0.008)
25–50 (1.00–2.00)	±0.40 (±0.016)
50–100 (2.00–4.00)	±0.70 (±0.028)
100–150 (4.00–6.00)	±1.00 (±0.040)

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